5 The New Capabilities of Weather Satellites

Introduction

Weather, or meteorological, satellites are in fact essentially remote-sensing satellites. What is an important distinguishing feature about this type of satellite application is that they are essentially all operated as governmental services that are supported by tax revenues rather than commercial revenues and services.

The economic challenge is that everyone wishes to benefit from the vital services that meteorological satellites provide, but there is no particularly viable way to offer this service on a strictly commercial basis. This type of satellite is representative of the classic problem in economics referred to sometimes as the lighthouse dilemma. It has always been the case that all ships at sea would like to have lighthouses to warn them of dangerous reefs, yet individual ship owners do not have the wherewithal to pay to build the lighthouses themselves. Thus many functions, whether it is lighthouses, construction of roadways and dams or supply of water have ended up as being offered as a governmental service.

In the United States, however, where private space services are under new analysis, there is consideration as to whether new commercial initiatives might possibly be used in the form of hosted payloads, or might be offered on a commercial basis in other ways. Thus while these type services might not be fully commercialized, as is the case with communications satellites, there may be future prospects to purchase some forms of meteorological data, provided on a supplementary basis by commercial systems.

Everyone one wishes to know about the weather. They especially want to be warned about violent and perhaps deadly storms and even about deadly solar storms such as dangerous coronal mass ejections that can damage power grids, pipelines and satellites. But again individuals are not in a position to pay for expensive weather satellites that today serve several key functions. Those functions are to monitor weather and give warning about dangerous storms, to monitor solar weather and dangerous solar storms, and to monitor climate change and provide warning against

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various dangers associated with the longer-term effects of a changing climate.

The development of meteorological satellite technology has been on a continuous upward curve of technological innovation for a half century. The satellite sensors have greatly improved in their ability to monitor weather patterns, to track lightning strikes and storm movement via global lightning mappers (GLMs), X-ray detectors and sounders. These devices are able to operate with great precision to aid in storm monitoring and to detect the direction of storms in virtual real time. And over time additional capabilities have been added. Beyond monitoring and prediction of weather and weather-related events, these now include: monitoring of climate change, monitoring of space weather and especially solar radiation and coronal mass ejections, monitoring of Earth's magnetosphere and even emerging communications for downed pilots, stranded ships at sea and support for search and rescue operations.

Further, there are now both low Earth orbit satellites and geosynchronous satellites that are deployed to work in concert to provide improved data via integrated global imaging. These integrated systems allows better short-, medium- and longer-term weather forecasting. In addition to civilian meteorological satellite services, which are globally shared and coordinated by nations that operate these systems, there are several satellite networks that are operated to support defense and military operations as well.

As more and more countries have developed and orbited their own meteorological satellite systems, this has led to increased coordination and sharing of information. Global cooperation is reflected in many ways, including the sharing of meteorological observations and technical data by means of the World Weather Watch (WWW) that was established through the good offices of the World Meteorological Organization (WMO). This cooperation has also been aided by the Committee on Earth Observation Satellites. Finally, the various space agencies that support the development and in some cases the operation of meteorological satellites have cooperative contingency agreements to insure the continuous flow of satellite images to allow global weather forecasts. Perhaps most notable in this respect was the agreement between Japan and the United States for the GOES-9 satellite to be leased to Japan on an interim basis [1].

The many countries that now operate meteorological satellite systems include the United States, Japan, China, India, Russia, South Korea and those of the European Union. As the effects of climate change have become better understood, additional capabilities have been added to meteorological satellite designs in order to be able to track information related to longer-term trends and to correlate meteorological data. This applies especially to "essential climate variables" (ESVs) and changes to El Nina and El Nino. There is a great deal of additional information collected via meteorological or remote-sensing satellites that we do not necessarily think about yet it is also of critical importance. This is information related to ocean levels, ocean temperatures, land and atmospheric pollution levels, ice and glacial coverage and vegetation cycles over time.

Important New Meteorological Tracking Capabilities

In many ways the optical instruments, CCDs, infrared sensors and radiometers used in remote-sensing activities are largely also common to those used on meteorological satellites. There are some new sensing devices that bring special new capabilities to the latest meteorological satellite networks. For example, the U. S. NOAA satellites have added some special new capabilities in 2017 and 2018.

One of the new capabilities that have been added to the most recent satellites such as the NOAA GOES R, T and U satellites are lightning mappers. These systems are able to determine by means of two new types of sensors the frequency and patterns of lightning strikes to determine the direction, speed of movement and intensity of storms with a much greater precision. They can also be used to aid transportation systems – particularly the safety of aircraft flight and pilot decision-making during storm conditions.

New instrumentation for lightning mapping that is being deployed within the GOES-R, T and U spacecraft includes both an Advance Baseline Imager and the Geostationary Lightning Mapper. These will provide significant economic savings and new levels of safety in terms of storm warnings and prevention of accidents in air and other transportation systems (see Fig. 5.1).

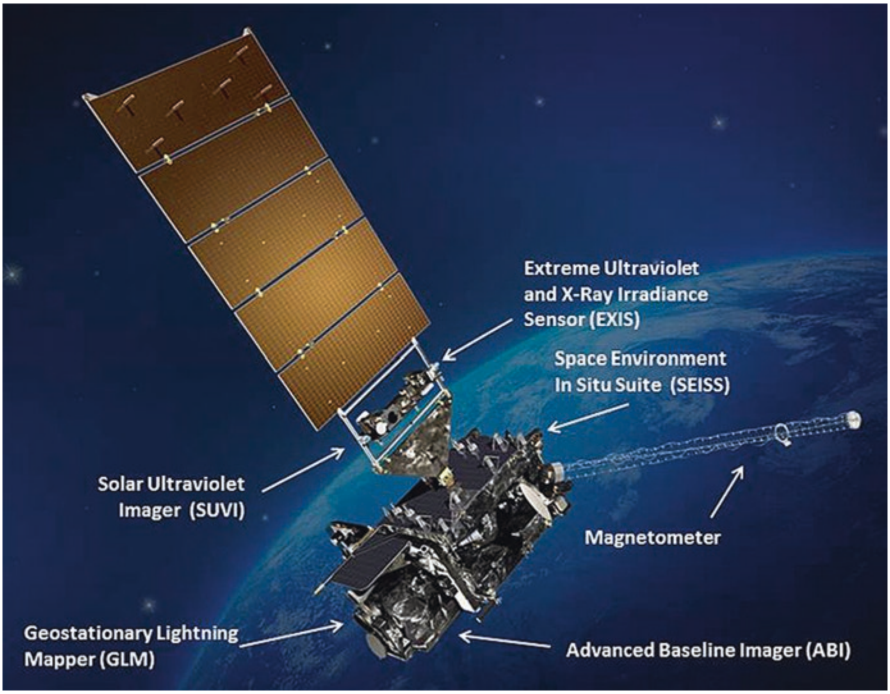

Fig. 5.1 The NOAA GOES-R satellite that features the new GLM and ABI sensors. (Illustration courtesy of NASA.)

The Advanced Baseline Imager (ABI)

The ABI is the primary instrument on GOES-R, T and U for imaging Earth's weather, climate and environment. The ABI on these satellites will provide coverage over a broad range of 16 different spectral bands. These bands include two visible channels, four near-infrared channels and ten thermal infrared channels. The ABI provides more spectral band coverage and higher spectral coverage than earlier types of imagers used on other meteorological satellites. The ABI has two main scan modes that can vary from full disk coverage to particular areas on demand with 30-second updates. Two new capabilities that come with the ABI improved sensing will be the ability to predict the likelihood of fog and its probable density as well as updates on changing storm conditions.

The ability to provided updates for particular targeted areas should greatly increase rapid-time response for coverage at special weather events that can range from thunderstorms, hurricanes, tornadoes, cyclones, to waterspouts. It can also provide targeted updates that relate to fires, volcanoes, or even areas affected by earthquakes. The other new feature that is included in the design is what is called the Geostationary Lightning Mapper (GLM) [2].

Geostationary Lightning Mapper (GLM)

The technical characterization of the Geostationary Lightning Mapper (GLM) is a near-infrared optical transient detector and imager. The GLM is capable of mapping lightning both for in-cloud and cloud-to-ground activity. The GLM is capable of providing a rapid indication of the strengthening of storms and initiating alerts concerning severe weather events. This capability is particularly able to provide improved tornado warnings with at least 20 to 30 minutes advanced notice. In addition, the lightning frequency data that is collected over a period of years can be processed to develop longer-term trend analysis that can be used in studies of climate variability.

It is anticipated that GLM data will have immediate applications to aviation weather services, climatological studies and severe thunderstorm forecasts and warnings. The GLM will provide information that is useful to climate change studies to help note changes in the number and magnitude of both destructive thunderstorms that occur both over land as well as in ocean areas. The U. S. National Oceanic and Atmospheric Administration (NOAA) has attempted to project the potential benefits of these satellites over their lifetime in terms of the warning and preventive precautions value of the ABI and GLM instruments and have indicated that these could be as much as $5 billion per satellite over the length of their in-orbit lifetime [3].

GLM measurements can provide vital information to help with operational preparedness and danger alerts for severe weather. These satellites support aviation, shipping, lightning strikes, fire monitoring and natural disaster reconnaissance.

These new capabilities will be seen in the meteorological satellite systems of many countries in future years. These advantages have been catalogued in the author's *Handbook of Satellite Applications* (2nd Edition), including at least the following features:

- An increased ability to develop short-range forecasts of heavy rainfall and flash flooding.
- New capability to provide near-real time detection of enhanced lightning activity that with associated improved models, can predict changes in the intensity change of tropical storms, hurricanes, and cyclones.
- Related improved warning capabilities for tornado and severe thunderstorm in terms of increased lead times as well as a corresponding reduction in false alarms and spurious information. (This particularly valuable new capability is of importance for storm warning and transportation routing for oceanic regions, mountain areas and areas where there might be radar outages.)
- Improved routing of commercial, military and private aircraft over oceanic regions, mountain areas and sparsely populated and remote areas during severe storm conditions.
- More accurate and timely warning of lightning ground strike hazards.
- Development of improved and more accurate numerical weather prediction models and increased identification of deep atmospheric convection patterns.
- Increased capability to develop what might be called "lightning climatology" and models of lightning intensity within storms.
- Improved ability to monitor and create mathematical models of a wide range of storm and lightning intensity patterns.

These capabilities, when combined with the capabilities on polar-orbiting satellites in low orbit, such as the U. S. POES and JPSS, provide an expanded range of abilities to: (i) forecast and better model weather events and climate change; (ii) assist with location of and recovery from natural disaster-related events, and (iii) help industry and communities to minimize the adverse effects of weather and natural disaster events by avoiding their worst effects and through better forecasting and prediction.

Monitoring of Terrestrial Gamma Ray Flashes (TGFs)

One of the unexpected benefits of lightning monitors on-board meteorological satellites has been a better understanding of terrestrial gamma ray flashes. It was at one time assumed that gamma ray flashes came either from the Sun or from cosmic sources at astronomical distances. The X-ray detectors, sounders, radiometers and spectrometers on-board meteorological satellites have confirmed that lightning flashes can give rise to X-rays and gamma radiation bursts. (See Fig. 5.2.)

The satellites that detected these types of very high energy events were never particularly designed for this purpose, and the more recent discoveries concerning this phenomenon have come from other sources. One of the most accurate sources of information about the characteristics of the very short-lived phenomena is the so-called Telescope Array, which is an observatory that is composed of 507 scintillation surface detectors. These detectors, which act as a sort of radio telescope,

Fig. 5.2 Lightning can release microsecond-long terrestrial gamma-ray flashes. (Graphic courtesy of NOAA.)

are spread out across a large distributed expanse of the Utah desert area. A report on the study of terrestrial gamma-ray flashes reports the following: "TGFs were originally measured by satellites, but the observations were imprecise. Thanks to the Telescope Array data, scientists now know the bursts last for a few dozen microseconds or less. The new data also proves TGFs originate in the thundercloud near the initial breakdown stage of the lightning" [4].

New Satellite-Based Monitoring of Essential Climate Variables (ECVs)

The earliest meteorological satellites were focused on weather imaging and forecasting, but it was soon discovered that the cumulative data from these satellites could aid understanding of climate trends. As satellite sensors grew in sophistication and as scientific precision grew, more and more capabilities were added to meteorological satellites. One of these important expanded capabilities was the addition to meteorological satellites of a sensor that could help to accumulate data related to monitoring climate change and to interpret longer-term shifts in the world's climate.

The deployment of satellites that were primarily designed to help predict weather did not always produce the data that was considered most vital to understanding longer-term effects related to climate change and obtaining key climatological data. Thus there have been a number of research satellites developed and launched by space agencies around the world. Appendix A in this book provides information with regard to some 34 satellites that have been launched to aid research into longer-term climatological changes. In some cases these satellite have played a dual role of providing operational data as well as research information and insight [5].

Keys to climatological research are two main factors. One factor is having data over a significant time period sufficient to identify longer-term trends. There are now in a number of cases data from observation satellites for a period of some 50 years. The second factor is to be able to assess the accuracy, reliability and quality of data from satellites, especially if taken from different satellites with different sensors that have variations in their design, sensitivity or calibration.

For the purpose of providing accurate and comprehensive climate monitoring data, a program known as SCOPE-CM was established a decade ago in 2008. SCOPE-CM stands for Sustained and COordinated Processing of Environmental satellite data for Climate Monitoring. SCOPE-CM represents a network of agencies and operators of environmental satellite systems that includes EUMETSAT, the Chinese Meteorological Administration, the Japanese Meteorological Agency and the U. S. National Oceanic and Atmospheric Administration, which also provides research data from NASA.

A number of key international agencies participate in this program. They include the World Meteorological Organization (WMO), the specialized agency of the United Nations, the World Climate Research Programme, which is a part of the World Climate Programme of the WMO, the Global Climate Observation System of the WMO, the Coordination Group for Meteorological Satellites (CGMS), the Committee on Earth Observation Satellites (CEOS), the Committee on Space Research (COSPAR) and other international groups that play a key role in climate observation. The purpose of SCOPE-CM is to support, coordinate and facilitate international activities to generate comprehensive and verifiable climate monitoring data from multi-agency satellite data.

Within SCOPE-CM, there are processes to develop data with respect to specifically identified climate monitoring categories that include such areas as carbon dioxide levels, methane levels, other greenhouse gas levels, sea level rise, desertification, global temperature increase, lakes, icecap coverage, etc. SCOPE-CM facilitates cooperation on the basis of shared and distributed responsibilities for the generation of global climate monitoring and essential climate variable products [6].

Closely associated with this process is the global initiative that is known as WG Climate. This activity has now created an effective mechanism for global sharing of climate-related data. The full name of WG Climate is "CEOS/CGMS Working Group on Climate." [7]

Solar Activity Monitoring and Dashboard Display in Near Real Time

The initial systems such as the NASA developed TIROS and Landsat satellites were focused on finding ways to use spacecraft to monitor weather conditions and carry out Earth observation. NASA, however, in its research missions also sought to carry out reconnaissance and research programs for the planets and the Sun. The costs of the Space Transportation System (STS) and the International Space Station (ISS) led to cutbacks in planetary and solar research projects. This not only resulted in the development of improved meteorological satellites but also promoted the idea of putting radiometers and other sensors on these spacecraft to monitor the Sun and solar weather as well as Earth weather.

Thus the meteorological satellites that NASA developed for NOAA increasingly included solar wind and radiation sensing capabilities. This pattern was also seen in the meteorological satellites that the space agencies developed in Russia (Meteor), Japan (GMS, Himawari) China (FengYun satellites) and India (Insat) with Sun-sensing capabilities.

The latest GEOS satellites, as represented by GEOS-R and shown in Fig. 5.1, contain a Space Environmental In Situ Suite (SEISS), a Solar Ultra-Violet (SUV) Imager and an Extreme Ultra-Violet and X-ray Irradiance Sensor (EXIS). These sensors allow NOAA to update a dashboard display on solar wind and alerts with regard to coronal mass ejections and solar flares. In fact the U. S. National Weather Service provides dashboard displays that include solar weather forecasts and near real time information that is specific to the areas of aviation, electric power, emergency management, global positioning systems, radio, satellites and even space weather (see Fig. 5.3) [8].

Improved Monitoring of Changes to Earth's Magnetosphere

Yet another aspect of meteorological satellite monitoring capabilities comes with respect to gathering data on Earth's magnetosphere. The ability of Earth to withstand massive solar weather storms actually depends on the world's magnetosphere. Earth's magnetic poles form a massive protective magnetic shield around the world. This is what shapes the Van Allen Belts. The magnetic shielding diverts ions from the Sun that travel at over a million kilometers per hour when spewed from the Sun during a coronal mass ejection. If it were not for this natural magnetic shielding the incoming high-energy ions would blast Earth's atmosphere and knock out electrical power systems and other infrastructure that range from pipelines, communications systems, to industrial control systems, to other satellites. When coronal mass ejections are forecast to hit Earth, satellites, electrical power systems, pipelines and many networks that depend on electrical energy power down to avoid massive outages. This problem and protective strategies against solar flares and coronal mass ejections are addressed in a later chapter.

A number of additional capabilities to study Earth's magnetosphere, such as the NASA's MagnetoMMS satellite mission, with a constellation of four satellites [9], and the ESA Swarm with a three-satellite constellation [10], are currently seeking to map the current shift in Earth's magnetosphere. These satellites have confirmed that a key shift in the magnetosphere is currently in progress. Magnetic north has now moved down to Siberia and magnetic south has moved up toward New Zealand.

This magnetospheric mapping exercise suggests that Earth's electronic grids around the world could be increasingly vulnerable to a major coronal mass ejection in coming years, as the natural

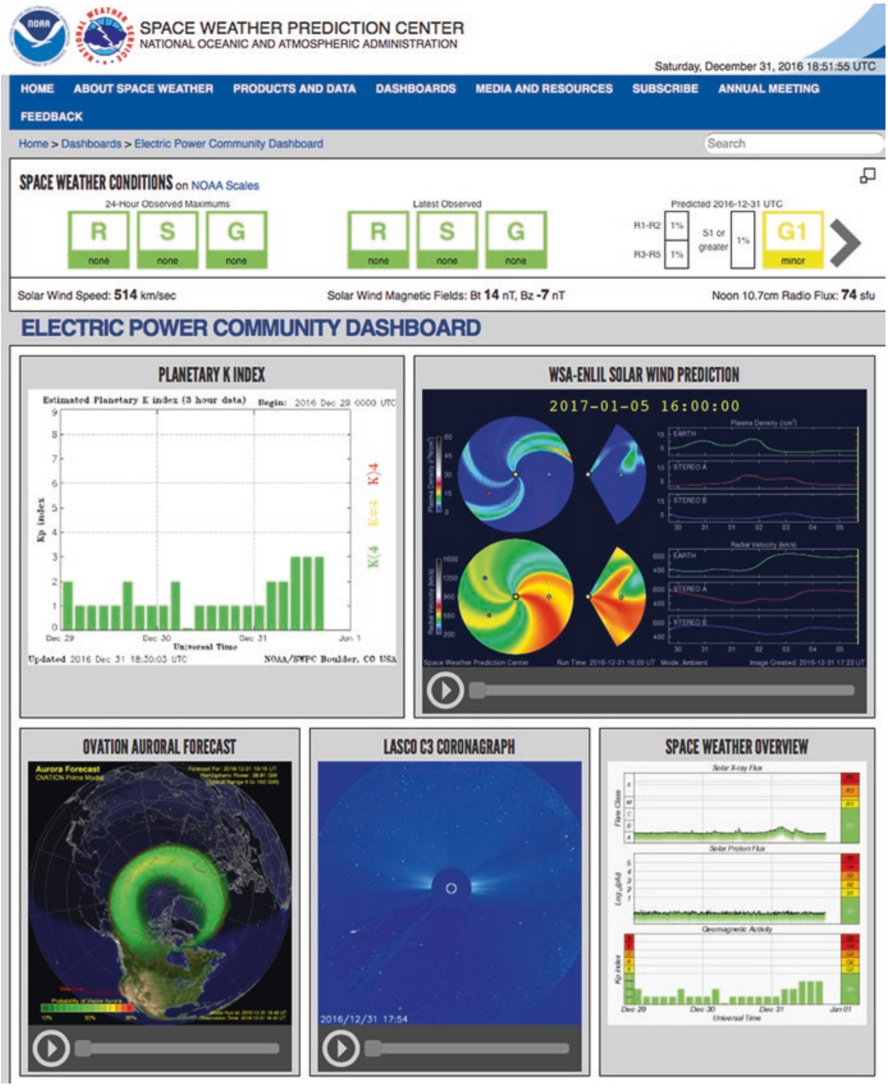

Fig. 5.3 NOAA National Weather Service dashboard display for electrical power. (Graphic courtesy of NOAA.)

protective shielding is reduced to a significant degree. If there should be a massive strike, similar to the Carrington Event of 1859, or even more recent events such as the Montreal Event of 1989 or the Halloween Event in Scandinavia of 2003 while Earth's natural shielding is down, the economic and infrastructure destruction consequences could be of catastrophic proportions and might require many years to recover from.

Emergency and Search and Recovery Communications

Finally, there is yet another aspect of meteorological satellite functionality, and this is to aid with search and rescue operations. GOES series satellites carry a payload supported by NASA's Search and Rescue (SAR) office, which researches and develops technologies to help first responders locate people in distress worldwide, whether from a plane crash, a boating accident or other emergencies. NASA has developed emergency beacons that are placed on most aircraft, ships and many vehicles operating in remote and perilous conditions. These beacons are automatically activated when an aircraft goes into the water or on severe impact.

There are three types of distress radio beacons that can be registered with COSPAS-SARSAT. These are the Emergency Location Transmitter (ELT) beacons for aviation use, the Emergency Position-Indicating Radio Beacons (EPIRBs) that are used for maritime applications, and the position location beacons (PLBs) for personal use. One of the great mysteries about the missing Flight 370 Malaysia aircraft is why the search and rescue ELT beacon did not work when it crashed. It should have immediately been activated and started transmitting as soon as the aircraft hit the water, and continued transmitting for a number of days.

The GOES is a geosynchronous satellite, and the GOES series thus has a global vantage point of the entire world. There are beacon relay systems on low Earth orbit satellites as well that can help target the site of a disaster with greater precision.

Many hundreds of crashed pilots and stranded crews and passengers on boats have now been rescued by means of the COSPAS-SARSAT beacons since this program began. This program also relies on the GNSS position location capabilities of the various satellite networks that participate in this program, which includes the U. S. GPS system and the Russian C [11].

Conclusions

The importance of meteorological satellites to the world economy as well as to human safety cannot be underestimated. The fact that these satellites provide a vital service in so many different areas is, however, not so widely understood. There is the apocryphal story about the Congressman that asked why there was a need to purchase expensive weather satellites when one could just turn on the weather channel to find out the latest weather conditions. Most people understand that weather information today comes from a combination of GEO and LEO satellites, aircraft and even drones and land-based instruments, but they likely are unaware of the sophisticated combination of sensors that provide images in the light spectrum as well as in the infrared up to the X-ray spectrum to understand weather conditions and the most severe of storms. Meteorological satellites can monitor lightning strikes, solar storms and flares, gamma ray events, help measure Earth's magnetosphere and relay signals from emergency search and rescue beacons.

Today a wide range of satellite activities and services have been commercialized, and their services in communications, networking, remote sensing, etc., represent a part of the global economy. Up to this time meteorological services have been provided as a governmental responsibility, but in the United States, at least, there is the possibility that some of these services might in the future be offered as hosted payloads on commercial satellite missions.

See the Addendum to this chapter in Appendix B at the end of this book for a list of current, past and proposed research satellites for climate-change purposes.

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